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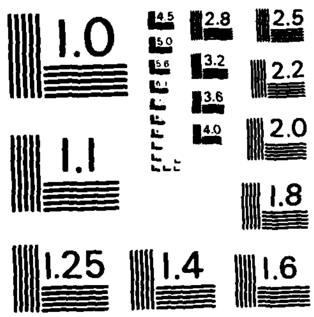

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AIR FORCE SYSTEMS COMMAND

FORM COEFFICIENT FOR THE FIELD OF A SUPERCONDUCTING SYNCHRONOUS MACHINE

by

A. I. Bertinov, A. V. Golovkin, et al.

FOREIGN TECHNOLOGY DIVISION

EDITED TRANSLATION

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Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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FORM COEFFICIENT FOR THE FIELD OF A SUPERCONDUCTING SYNCHRONOUS MACHINE

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The magnetic field of a superconducting synchronous machine is considered, an expression unique for all areas, is obtained for the radial component of intensity of the magnetic field, and the form coefficient of the field is determined.

The industrial assimilation of superconducting materials with high values of critical magnetic field led to the development of magnetic systems which can be used for excitation of electrical machines [1].

The use of superconductor excitation windings for synchronous machines leads to new structural arrangements for making them, and the absence of a ferromagnetic magnetic circuit complicates the picture of distribution of the magnetic field. What was said requires the refinement of the bases of the theory and methods of designing superconducting machines.

In [2] a magnetic field is considered which is created by the superconductor excitation winding of a synchronous machine, and in this case the component of strength of the magnetic field is presented in the form of infinite series, and only the first harmonic component is analyzed, which is not always justified.

A significant shortcoming of work [2] is that for each zone of the system its own expressions are obtained: inside the system, in the zone occupied by currents, and outside the excitation system. The absence of a generality - a unique expression - complicates their use, especially in the case of calculation on a digital computer.

In the present work a unique expression is obtained for finding the radial component of strength of a magnetic field in a finite form, and the form coefficient is determined for the field of a superconducting synchronous machine.

Let us consider the magnetic system of excitation of a synchronous machine which is shown in Figure 1. The problem of determination of the components of the vector of strength of the magnetic field in all the points of space in respect to an assigned distribution of current is solved by finding the vector potential of the magnetic field as a function of the coordinates:

$$\left.\begin{aligned} A &= \frac{\mu_0}{4\pi}\int_v \frac{j\,dv}{a}, \\ H &= \frac{1}{\mu_0}\,\mathrm{rot}\,A. \end{aligned}\right\} \qquad (1)$$

In solving the problem the following assumptions are accepted: the magnetic field is plane-parallel, i.e, the finite length of the excitation system is not taken into account; the magnetic permeability of the superconducting material of the excitation winding is constant and equal to μ_0 , since the superconducting materials in magnetic systems operate with fields which are close to critical; the area occupied by currents is uniform.

Then in a cylindrical system of coordinates the axial component of the vector potential function in point P(ρ , φ) from the elementary conductor with current, found in point M(r, φ_0), is equal to

$$A = -\frac{\mu_0}{2\pi} j_{cp} r\, d\varphi_0\, dr \ln a, \qquad (2)$$

where $a = \sqrt{\rho^2 + r^2 - 2\rho r\cos(\varphi - \varphi_0)}$.

$j_{cp} = \frac{I}{q_{c.з.п}} k_{з.п}$ - average calculated density of current;

I - current, passing on a conductor;

$q_{c.з.п}$ - area of the transverse section of the superconducting conductor;

$k_{з.п} = \frac{q_{c.з.п} w}{q_{об}}$ - space factor of the superconductor in the excitation winding;

w - number of turns in the winding;

$q_{об}$ - area of transverse section occupied by the excitation winding.

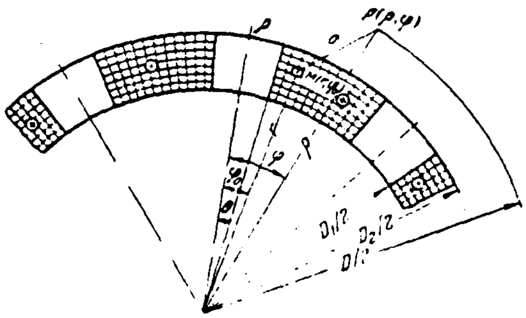

Figure 1. Excitation winding of a superconductor synchronous machine.

The radial component of strength of the magnetic field from an elementary conductor with current

$$H'_\rho = \frac{1}{\mu_0 \rho} \frac{\partial A}{\partial \varphi} = -\frac{j_{cp} r^2 \sin(\varphi - \varphi_0)\, dr\, d\varphi_0}{2\pi\left[\rho^2 + r^2 - 2\rho r \cos(\varphi - \varphi_0)\right]}. \qquad (3)$$

Let us integrate on the entire section occupied by the individual coils with current, with a calculation of the number of pairs of poles

p and $\gamma = \frac{\pi - 2\theta}{\pi}$:

$$H_\rho = -\frac{j_{cp}}{2\pi} \sum_{k=1}^{k=2p} (-1)^{k+1} \times$$

$$\times \int_{\frac{D_1}{2}}^{\frac{D_2}{2}} \int_{\pi\left(\frac{k-1}{p} + \frac{1-\gamma}{2}\right)}^{\pi\left(\frac{k}{p} - \frac{1-\gamma}{2}\right)} \frac{r^2 \sin(\varphi - \varphi_0)}{\rho^2 + r^2 - 2\rho r \cos(\varphi - \varphi_0)}\, dr\, d\varphi_0. \qquad (4)$$

After integration, replacement of $\rho = D/2$ and introduction for convenience of subsequent calculations and construction of the graphic dependences of relative dimensions

$$\mathring{D}_1 = \frac{D_1}{D_2}; \; \mathring{D} = \frac{D}{D_2}$$

we obtain:

$$H_p = \frac{I_{sp} D_2}{8\pi} K_p,$$

where the coefficient

$$\begin{aligned}
K_p = \sum_{k=1}^{k=2p} (-1)^{k+1} \Bigg[& \frac{1}{2\mathring{D}} \ln \frac{\mathring{D}^2 + 1 - 2\mathring{D}\cos\alpha}{\mathring{D}^2 + 1 - 2\mathring{D}\cos\beta} - \\
& - \frac{\mathring{D}_1^2}{2\mathring{D}} \ln \frac{\mathring{D}^2 + \mathring{D}_1^2 - 2\mathring{D}\mathring{D}_1\cos\alpha}{\mathring{D}^2 + \mathring{D}_1^2 - 2\mathring{D}\mathring{D}_1\cos\beta} - \mathring{D}\left(\cos^2\alpha - \frac{1}{2}\right) \times \\
& \times \ln \frac{\mathring{D}^2 + 1 - 2\mathring{D}\cos\alpha}{\mathring{D}_1^2 - 2\mathring{D}\mathring{D}_1\cos\alpha} + \mathring{D}\left(\cos^2\beta - \frac{1}{2}\right) \times \\
& \times \ln \frac{\mathring{D}^2 + 1 - 2\mathring{D}\cos\beta}{\mathring{D}^2 + \mathring{D}_1^2 - 2\mathring{D}\mathring{D}_1\cos\beta} + (1 - \mathring{D}_1)(\cos\beta - \cos\alpha) + \\
& + \mathring{D}\sin 2\alpha \left(\operatorname{arctg} \frac{1 - \mathring{D}\cos\alpha}{\mathring{D}\sin\alpha} - \operatorname{arctg} \frac{\mathring{D}_1 - \mathring{D}\cos\alpha}{\mathring{D}\sin\alpha} \right) - \\
& - \mathring{D}\sin 2\beta \left(\operatorname{arctg} \frac{1 - \mathring{D}\cos\beta}{\mathring{D}\sin\beta} - \operatorname{arctg} \frac{\mathring{D}_1 - \mathring{D}\cos\beta}{\mathring{D}\sin\beta} \right);
\end{aligned}$$

$$\alpha = \varphi - \pi\left(\frac{k}{p} - \frac{1-\gamma}{2}\right); \quad \beta = \varphi - \pi\left(\frac{k-1}{p} + \frac{1-\gamma}{2}\right). \qquad (5)$$

Expression (5) is valid for any point of the area under consideration.

For determination of the form coefficient of the field it is necessary to have an expression for the maximum of the radial component of magnetic field strength, which will be in the case of the angle $\varphi = 0$, in this case

$$\alpha = -\pi\left(\frac{k}{p} - \frac{1-\gamma}{2}\right); \quad \beta = -\pi\left(\frac{k-1}{p} + \frac{1-\gamma}{2}\right).$$

With complete filling of the active layer by the winding $\theta=0$ and $\gamma=1$. In this case

$$a=-\frac{\pi k}{p} \text{ and } \beta=\alpha+\frac{\pi}{p}.$$

Thus, with $\gamma=1$ and different numbers of pairs of poles it is possible to write:

when $p=1$

$$K_p=\frac{2}{\dot{D}}(1-\dot{D}^2)\ln\frac{\dot{D}+1}{\dot{D}-1}-\frac{2}{\dot{D}}(\dot{D}_1^2-\dot{D}^2)\ln\frac{\dot{D}+\dot{D}_1}{\dot{D}-\dot{D}_1}+$$

$$+4(1-\dot{D}_1);$$

when $p=2$

$$K_p=\frac{2}{\dot{D}}\ln\frac{\dot{D}^2+1}{\dot{D}^2-1}-\frac{2\dot{D}_1^2}{\dot{D}}\ln\frac{\dot{D}^2+\dot{D}_1^2}{\dot{D}^2-\dot{D}_1^2}+$$

$$+2\dot{D}\ln\frac{\dot{D}^4-1}{\dot{D}^4-\dot{D}_1^4};$$

when $p=3$

$$K_p=\frac{1}{\dot{D}}(1+\dot{D}^2)\ln\frac{\dot{D}^3+1}{\dot{D}^3-1}+3\dot{D}\ln\frac{\dot{D}-1}{\dot{D}+1}-$$

$$-\frac{1}{\dot{D}}(2\dot{D}_1^2+\dot{D}^2)\ln\frac{\dot{D}^3+\dot{D}_1^3}{\dot{D}^3-\dot{D}_1^3}-3\dot{D}\ln\frac{\dot{D}-\dot{D}_1}{\dot{D}+\dot{D}_1}+$$

$$+2\sqrt{3}\dot{D}\left[\operatorname{arctg}\frac{2-\dot{D}}{\sqrt{3}\dot{D}}+\operatorname{arctg}\frac{2+\dot{D}}{\sqrt{3}\dot{D}}-\right.$$

$$\left.-\operatorname{arctg}\frac{2\dot{D}_1-\dot{D}}{\sqrt{3}\dot{D}}-\operatorname{arctg}\frac{2\dot{D}_1+\dot{D}}{\sqrt{3}\dot{D}}\right];$$

when $p=4$

$$K_p=\frac{2}{\dot{D}}\ln\frac{\dot{D}^4+1}{\dot{D}^4-1}+2\dot{D}\ln\frac{\dot{D}^2-1}{\dot{D}^2+1}-$$

$$-\frac{2\dot{D}_1^2}{\dot{D}}\ln\frac{\dot{D}^4+\dot{D}_1^4}{\dot{D}^4-\dot{D}_1^4}+2\dot{D}\ln\frac{\dot{D}^2+\dot{D}_1^2}{\dot{D}^2-\dot{D}_1^2}+$$

$$+4\dot{D}\left[\operatorname{arctg}\frac{2-\sqrt{2}\dot{D}}{\sqrt{2}\dot{D}}-\operatorname{arctg}\frac{2+\sqrt{2}\dot{D}}{\sqrt{2}\dot{D}}-\operatorname{arctg}\frac{2\dot{D}_1-\sqrt{2}\dot{D}}{\sqrt{2}\dot{D}}+\right.$$

$$\left.+\operatorname{arctg}\frac{2\dot{D}_1+\sqrt{2}\dot{D}}{\sqrt{2}\dot{D}}\right].$$

The dependences $K_\rho = f(D^*$ and $D^*_1)$ in respect to p are given in Figure 2. Coefficient K_ρ is proportional to the radial component of magnetic field strength, and from these graphs it follows that the radial component of magnetic field strength has the greatest value inside the area occupied by the excitation winding. With the same dimensions of the excitation winding the maximum value of magnetic field strength which is obtained is greater in two-pole machines and is reduced with an increase in the number of pairs of poles of the excitation winding.

Using (5) and having assigned the dimensions of the excitation winding and the armature, it is possible to determine the emf induced in the armature winding. As it follows from [2], the amplitude of the curve of the harmonic component of magnetic field intensity is expressed for different areas with $\gamma = 1$:

for

$$\mathring{D} < \mathring{D}_1$$

$$H_{\rho 1m} = \frac{i_{cp} D_2}{8\pi} \frac{8(1 - \mathring{D}_1^{-p+2})}{(2-p)\mathring{D}^{-p+1}};$$

for

$$\mathring{D}_1 < \mathring{D} < 1$$

$$H_{\rho 1m} = \frac{i_{cp} D_2}{8\pi} \frac{8\mathring{D}}{4-p^2}\left[-2p + \frac{2+p}{\mathring{D}^{-p+2}} - \frac{(2-p)\mathring{D}_1^{p+2}}{\mathring{D}^{p+2}}\right]\mathring{D};$$

for

$$1 < \mathring{D}$$

$$H_{1\rho 1m} = \frac{i_{cp} D_2}{8\pi} \frac{8(1 - \mathring{D}_1^{p+2})}{(p+2)\mathring{D}^{p+1}}.$$

Thus it is possible to determine the form coefficient for the field of a superconductor machine with $\gamma = 1$:

$$K_f = \frac{H_{\rho 1 \varphi = 0}}{H_{\rho \varphi = 0}},$$

shown in Figures 3 and 4 in dependence on $\overset{*}{D}$ and $\overset{*}{D}_1$ for different numbers of pairs of poles.

An analysis of the graphs in Figures 3 and 4 shows that the ratio of the maximum of magnetic field strength to the amplitude of the first harmonic component reaches 1.8, therefore disregard of the higher harmonic components, especially in the case of calculation inside the coil, is inadmissible.

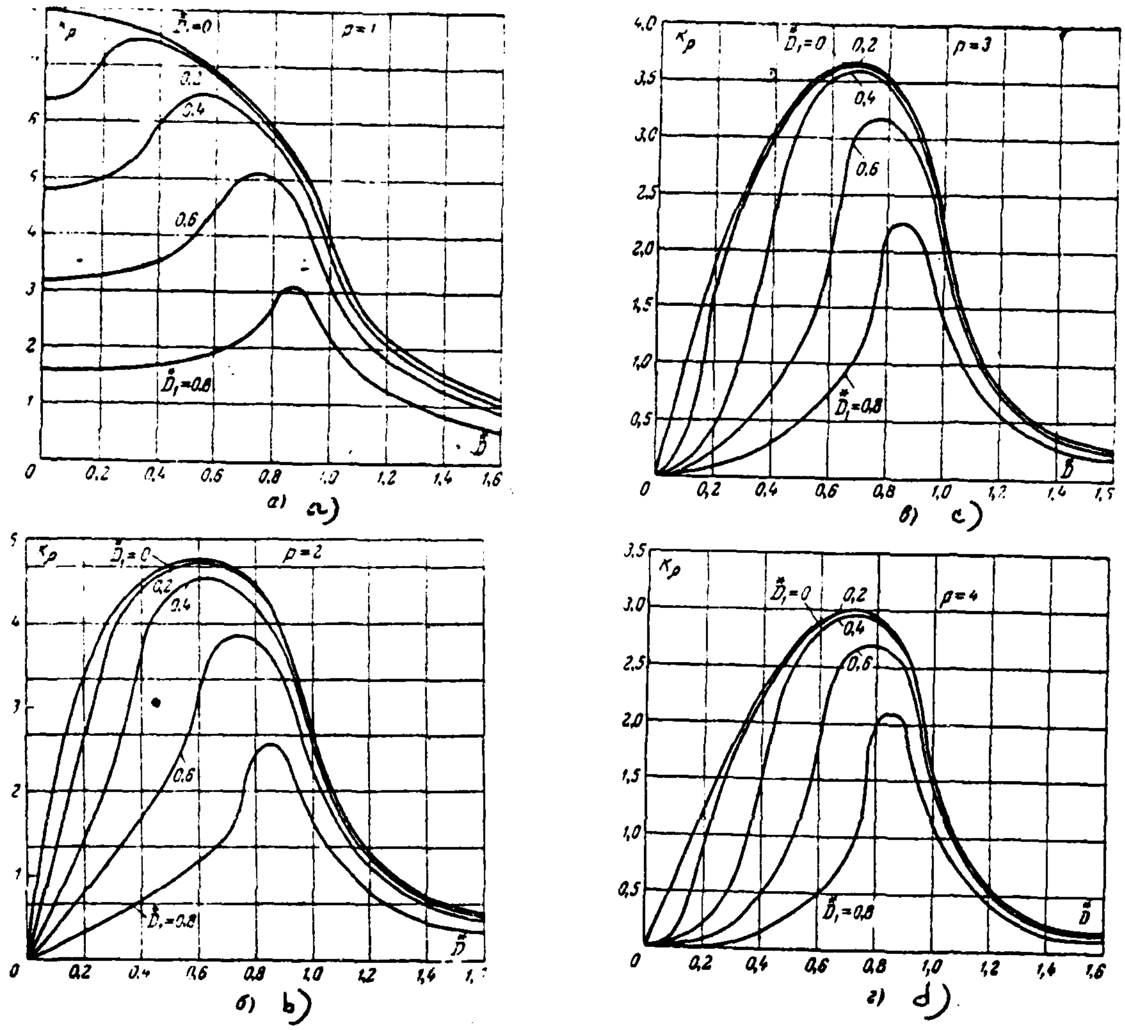

Figure 2. Dependence of $K_\rho=f(\overset{*}{D})$ in respect to $\overset{*}{D}_1$.

а — $p = 1$; б — $p = 2$; в — $p = 3$; г — $p = 4$.

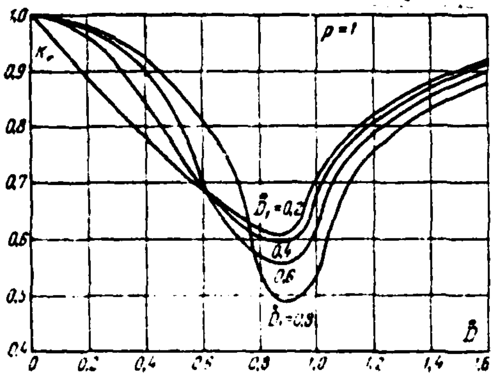

Figure 3. Dependence of $K_f = f(\overset{*}{D})$ in respect to $\overset{*}{D}_1$ when p=1.

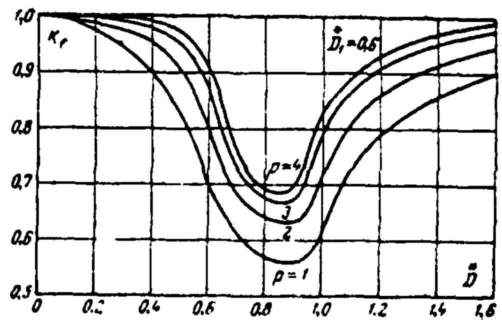

Figure 4. Dependence of $K_f = f(\overset{*}{D})$ in respect to p when $\overset{*}{D}_1$=0.6.

Conclusions.

1. A unique expression is obtained for the radial component of magnetic field strength for any area of a system of excitation.

2. The form coefficient of the field of the excitation winding is obtained.

3. Analysis showed the considerable magnitude of the higher harmonic components of magnetic field strength in the area occupied by currents.

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